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Evaluation of Ebb-Tidal Shoals as a Sand Source for Beach Nourishment: General Methodology with Reservoir Model Analysis

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Abstract

Morphologic features of tidal inlets, such as ebb shoals and flood shoals, are attractive potential sources of sediment for beach nourishment because of their close proximity to shore and the probable compatibility of sediment grain size and color with those of the neighboring beaches. Removal of sediment by mining will, however, interrupt the natural sediment bypassing of the integrated sediment-sharing system. Until recently, the consequences of mining inlets were difficult to estimate. The Inlet Reservoir Model is a new technology that can estimate alterations in growth of inlet morphologic features and changes in the bypassing rate in response to mining of ebb- and flood-tidal shoals. This paper describes a general methodology incorporating bathymetric data and aerial photography, operation of wave and tidal circulation numerical models, and application of the Reservoir Model to examine the response of complex inlet system, Capri Pass, Florida, to proposed sediment mining to nourish the downdrift Hideaway Beach. The Reservoir Model provided estimates of the reduction in natural bypassing and the time lag for recovery to the pre-mining condition. Through application of such a methodology, which is applicable to any tidal inlet, alternatives for the location of mining and acceptable amount of volume to be taken can be evaluated and compared quantitatively.

INTRODUCTION

Ebb shoals typically contain substantial quantities of beach-quality material and offer a potentially significant economic advantage as a borrow source over offshore sources because of proximity to the beach. However, ebb shoals are part of an interactive morphologic system that evolves towards dynamic equilibrium under sediment transport produced by waves and tidal currents. Mature ebb shoals allow a maximum amount of sand to bypass an inlet to the downdrift beach. Mehta, et al. (1996) reviewed the acting processes, listed inlets in Florida where ebb shoals have been mined, and identified needs for predictive technology to assess the consequences of ebb-shoal mining.

Dredging of inlets for navigation channel maintenance and mining of ebb shoals for beach nourishment interrupts natural bypassing and may contribute to inlet-related beach erosion. Cialone and Stauble (1998) reviewed eight ebb-shoal mining projects on the Atlantic and Gulf coasts. Their analysis indicates varying responses ranging from beneficial to detrimental. The main detrimental impact was chronic downdrift beach erosion at some sites. Mixed outcomes of previous projects and lack of tools to assess consequences make potential for adverse consequences of ebb-shoal mining a concern to permitting agencies. As a result, regulatory agencies may be cautious and resist or reject proposed use of ebb shoals as a sand source.

Challenges in sand management near inlets include the complexity of coastal processes at inlets and lack of guidelines and tools to quantify the various responses of the system to mining of ebb shoals and channel dredging for beach nourishment. Timeframes for such responses are a central factor because, in dealing with large sand shoals, adjustment in bypassing and morphology may require many years. Monitoring programs and mitigation measures must be designed with awareness of these long time lags.

Research is underway to establish practical modeling tools and guidelines for access to ebb shoals as sand sources. The Inlet Reservoir Model (Kraus 2000a, 2000b) is such a new analytical tool developed to quantify volume change of inlet features and sediment pathways at ebb-tidal and related inlet shoals. The model provides estimates of ebb-shoal evolution and natural bypassing rates at inlets. It can also predict the time response of the bypassing rate and shoal recovery rate as a consequence of ebb-shoal mining (and flood-shoal mining). The model has been applied to address engineering issues at several sites, including Ocean City Inlet, Maryland (Kraus 2000a,b), Shinnecock Inlet, New York, (Militello and Kraus 2001), Fire Island Inlet, New York (Kraus et al. 2003), and Sebastian Inlet, Florida (Zarillo, et al. 2003).

This paper presents an application of the Inlet Reservoir Model to a complex inlet system. A general approach is taken in applying a variety of engineering models and analysis procedures to evaluate the morphologic evolution and bypassing of Capri Pass, Florida. The analysis assesses the potential of its ebb shoal as a sand source for restoration of the down-drift beach, Hideaway Beach.

BACKGROUND

Capri Pass is the major tidal inlet of a multi-inlet system that includes Little Marco Pass, Capri Pass, and Big Marco Pass (Figure 1). The three inlets connect Johnson Bay and Big Marco River to the Gulf of Mexico. Capri Pass and Big Marco Pass have been regarded as a dual inlet system (Van de Kreeke 1990) because the two inlets are separated by a small island (Coconut Island) and by a large and complex ebb shoal system. Large-scale changes in this inlet system over the past five decades have influenced the evolution of Hideaway Beach (Humiston 1988). Hideaway Beach is located between Royal Marco Point and South point on the northwest end of Marco Island along the Gulf of Mexico coastline.

Figure 1. Project location

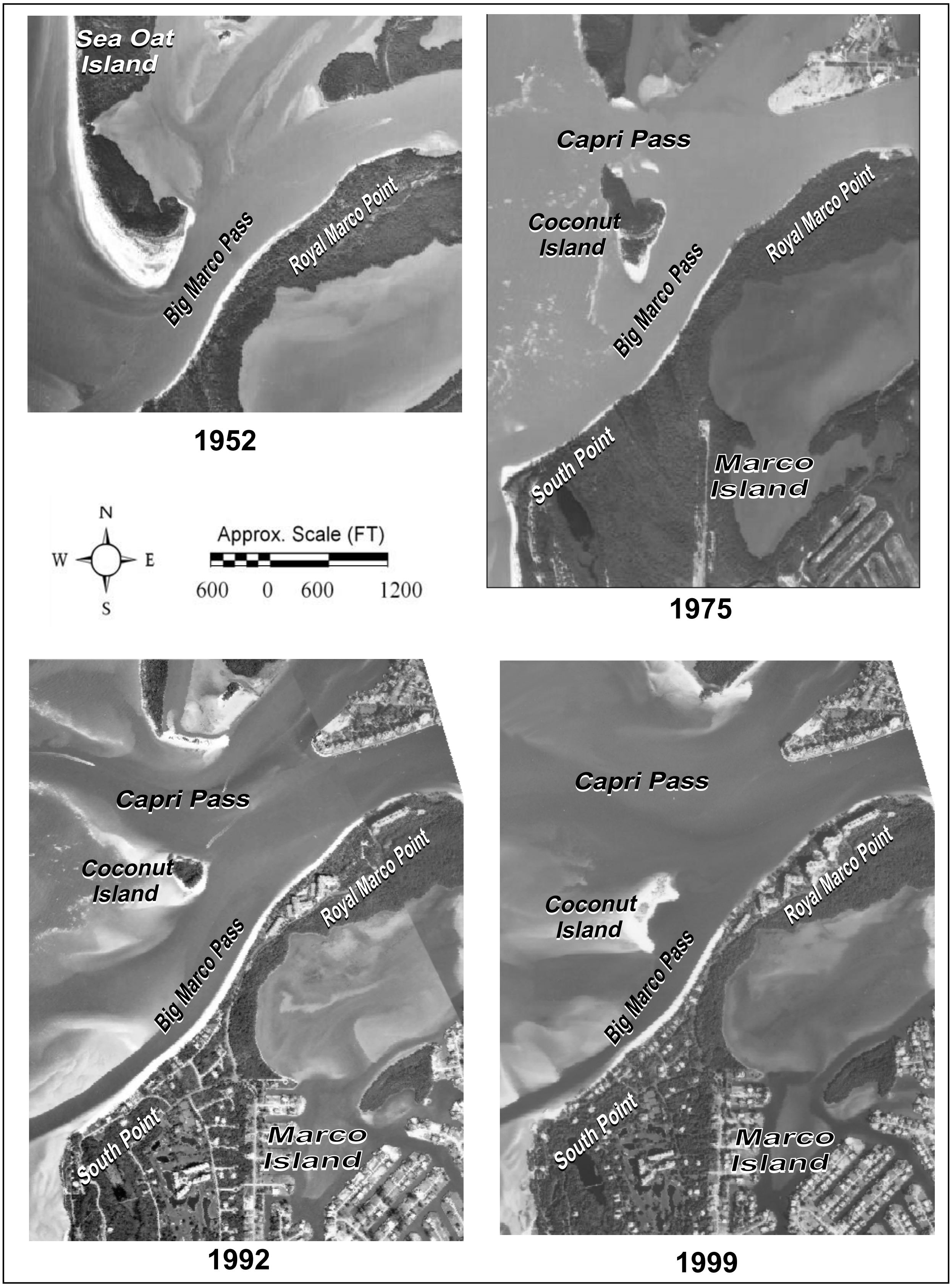

Figure 2. Photographic documentation inlet evolution

Selected aerial photographs of Capri Pass and Big Marco Pass inlet system from 1952 to 1999 are arranged in Figure 2. As shown in the 1952 photograph, Coconut Island was part of Sea Oat Island, and Big Marco Pass was the only inlet. At that time, Big Marco Pass carried all of the tidal flow, as well as freshwater discharge from the Big Marco River. The tidal prism is estimated to be approximately 1,200 million cu ft on an average tide (Van de Kreeke 1990). In 1967, Capri Pass opened approximately 2,000 ft to the north of Big Marco Pass.

Since that time, Capri Pass has continued to increase in size as it captures greater shares of the tidal and fresh water flows. In the process, Coconut Island and Sea Oat Island eroded, and some of that sand was deposited on the new ebb shoal forming around Capri Pass. This shift in flow from Big Marco Pass to Capri Pass has resulted in the ebb shoal of Big Marco Pass migrating towards Marco Island. By 1990, Coconut Island had been reduced to approximately 10% of its 1967 area. However, during the following years, Coconut Island started to regain volume while continuing to migrate southwest.

By 1996, the width of Capri Pass was approximately 2,000 ft, which exposed Royal Marco Point to waves incident from the Gulf of Mexico. The wave energy window, as illustrated in Figure 3, generated unidirectional sediment transport from west to east with little supply of sediment from the west due to the presence of a shadow zone from Coconut Island and the shoal system. By 1997, the growth and migration of Coconut Island created a large shadow zone on Hideaway Beach that reduced sand supply toward royal Marco Point. Monitoring in year 2000 showed that Coconut Island continued to migrate southwest and Sea Oat Island continued to erode as the width of Capri Pass increased from about 2,000 ft to approximately 3,200 ft. Hydrodynamic modeling results for this regional multi-inlet system indicate that the percentages of tidal prism flowing through Little Marco Pass, Capri Pass, and Big Marco Pass are 7, 90, and 3% respectively.

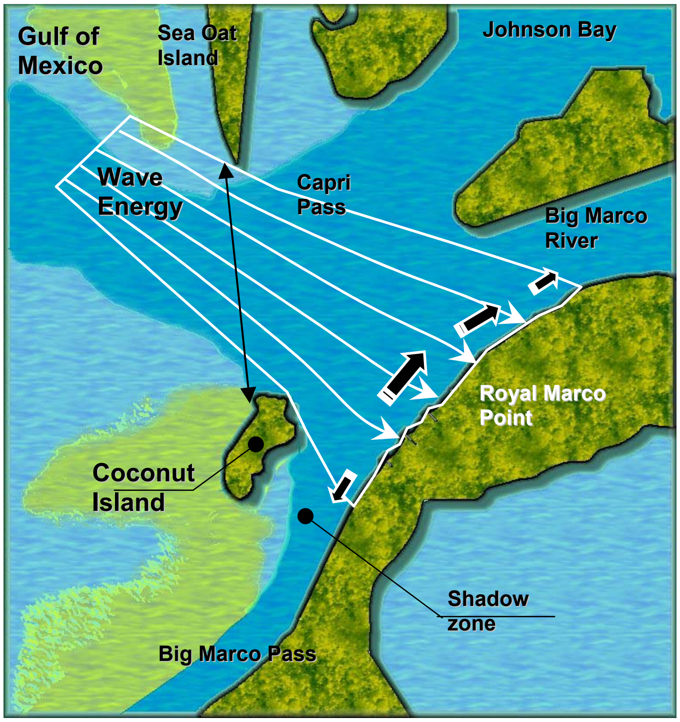

Figure 3. Illustration of wave energy and sediment transport at Royal Marco point (1996 conditions)

REGIONAL MORPHOLOGIC FEATURES

Regional and local surveys covered the inlet system for 1994, 2000, and 2003. Figure 4 gives a perspective view of the inlet system and distinct features. The figure shows the multiple channels and large size of Capri Pass compared to the narrower and longer channels of Little Marco Pass and Big Marco Pass. The quality and extent of the data sets allowed identification of distinct morphologic features that appeared in all data sets. In addition, Comparisons between data sets quantified elevation change and evolution trends in the ebb-shoal features. Figure 5 shows the elevation change between 1994 and 2003, indicating the deepening and widening of Capri Pass, growth of the ebb shoal features, and sedimentation (shoaling) of big Marco Pass. The figure also illustrates the migration of Coconut Island (the small island that separates Capri Pass and big Marco Pass) towards Marco Island. The collapse of the derelict shoal of big Marco Pass supplying sand to the attachment bar (Sand Dollar Island) is also seen.

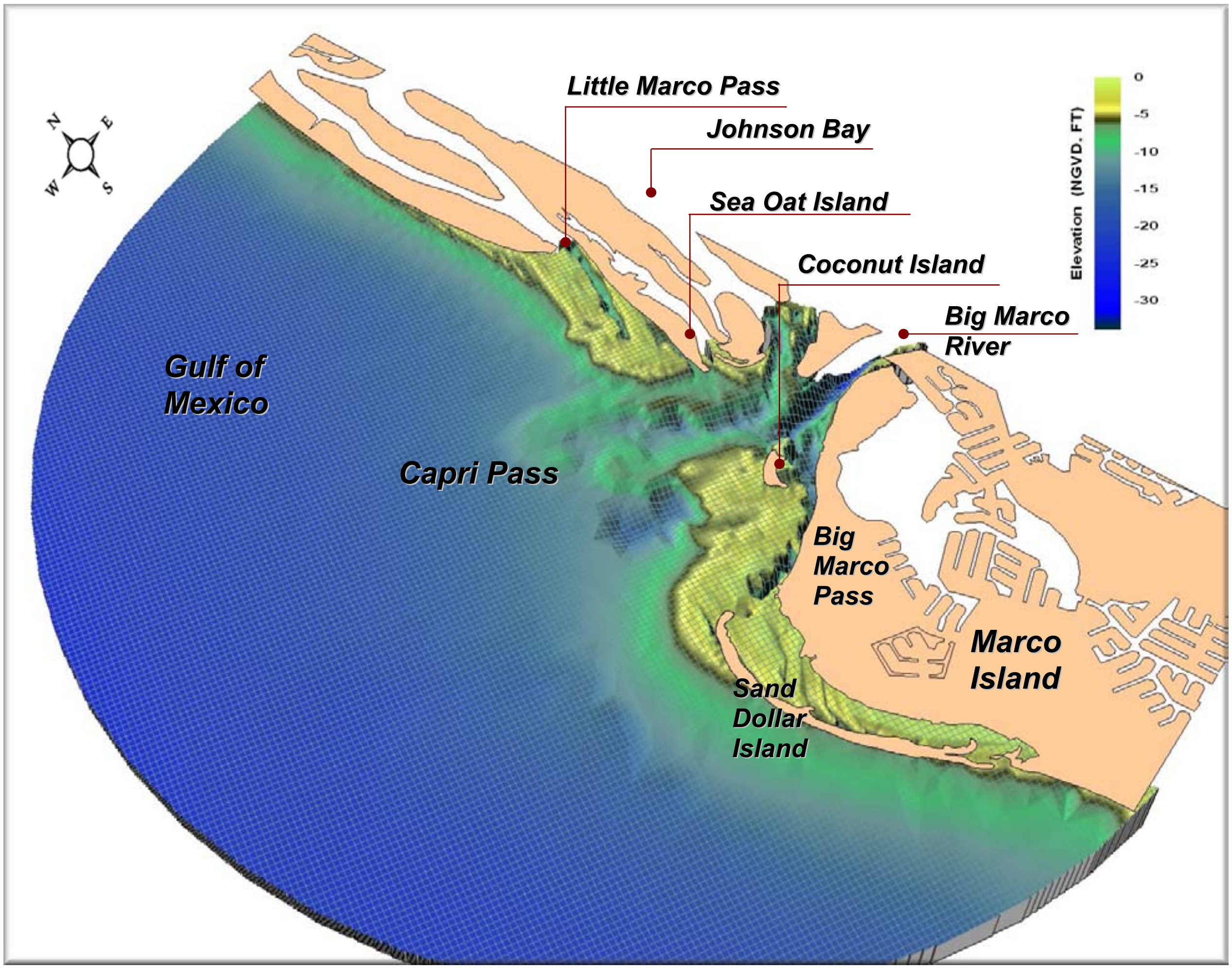

Figure 4. Regional features of the inlet system (2003 condition)

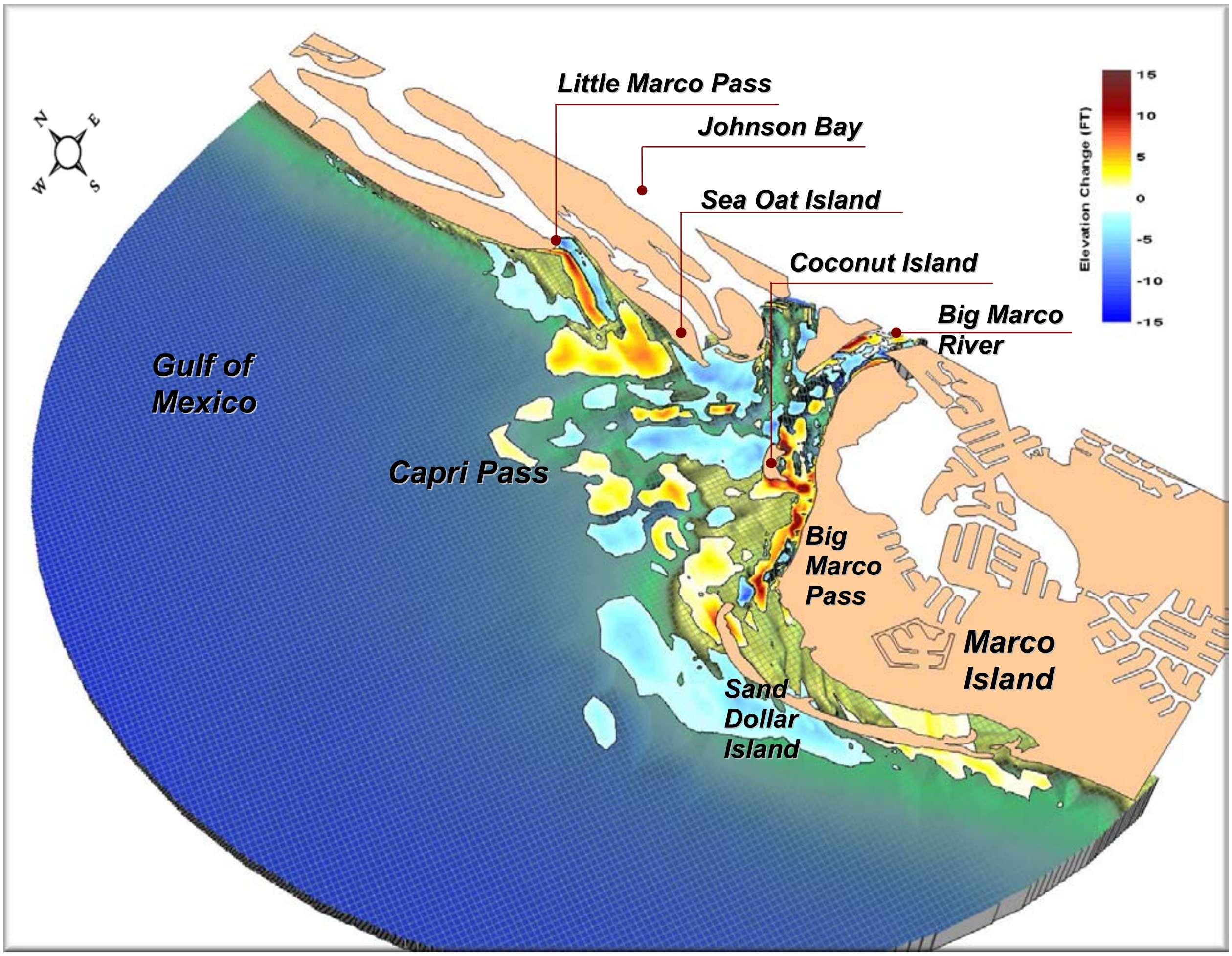

Figure 5. Regional elevation changes (1994-2003)

Coconut Island

Coconut Island is selected for discussion, as it represents a significant feature in the evolution of the inlet system and sediment pathways. Coconut Island is a small island located between two tidal inlets and exposed to direct wave action from the Gulf of Mexico. The evolution of Coconut Island has direct bearing on the fate of Hideaway Beach as described in the Background section. Wave and tidal current modeling were performed to evaluate the forces that are influencing the morphologic evolution of Coconut Island. Since 1998, Coconut Island shoreline has been approximately 1,000 ft long with an orientation normal to the predominantly NW window of wave exposure. From 1998 until 2003, Coconut Island shoreline has steadily receded parallel to itself, at a rate of 32 ft/year, while forming growing spits at both ends (Figure 6).

Figure 6. Coconut Island shoreline positions (1998-2003)

Wave refraction modeling explains this process. When wave arrive from N to NW, their breaking drives sediment transport to the SW, eroding the shoreline and forming the SW spit (Figure 7). On the other hand, when wave arrive from W and SW, the sediment transport along Coconut Island shoreline is towards the NW, forming the other spit (Figure 8). Because the predominant wave direction is from NW, the SW spit is larger than the NW spit of Coconut Island. The wave analysis and sediment transport for this area are given in Dabees et al. (2002) and H&M (2003). The analysis indicates that without the presence of tidal currents, Coconut Island might have been over-washed by waves and attached to Hideaway Beach. However, strong tidal currents through Big Marco Pass are still preventing Coconut Island from attaching to Hideaway Beach (Appendix A). Circulation modeling results indicate that tidal currents at the SW spit of Coconut Island are sufficiently strong to prevent Coconut Island from attaching. The results also show the ebb current through Big Marco Pass flows more around Coconut Island into the Gulf rather than through the channel of Big Marco Pass. The calculated circulation pattern explains the sedimentation (shoaling) of Big Marco Pass and reduced share of tidal prism flowing through it.

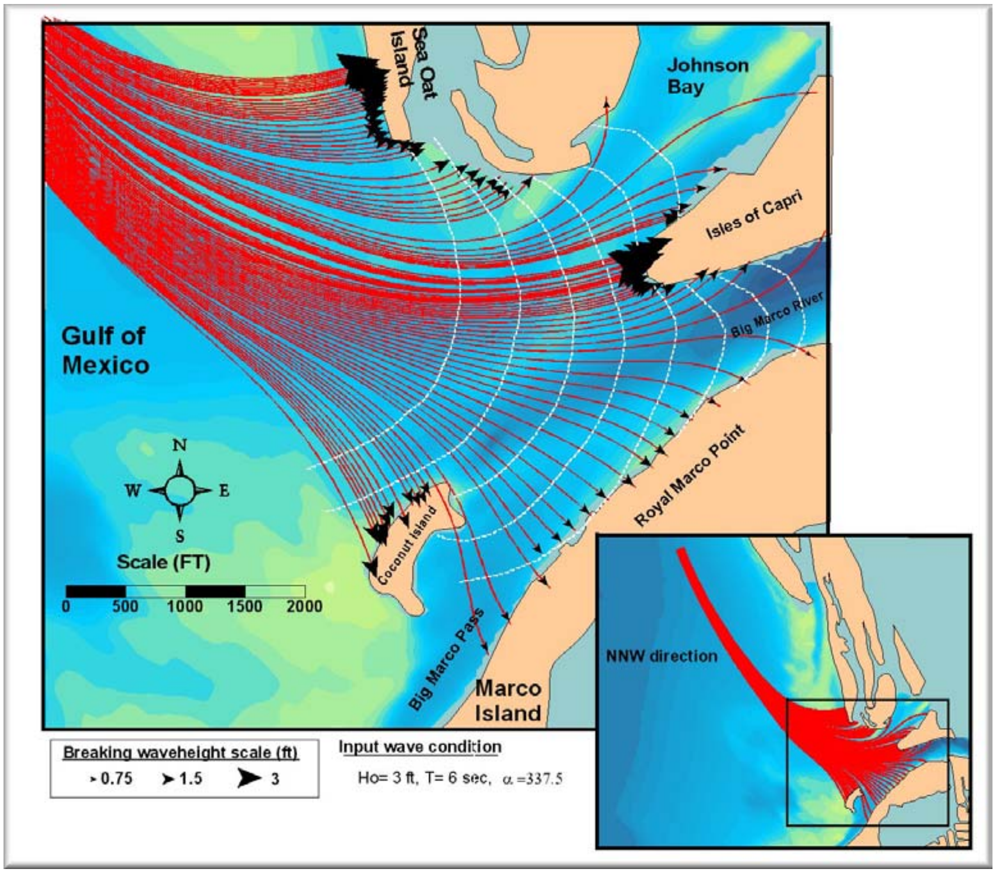

Figure 7. Wave refraction results for NNW direction

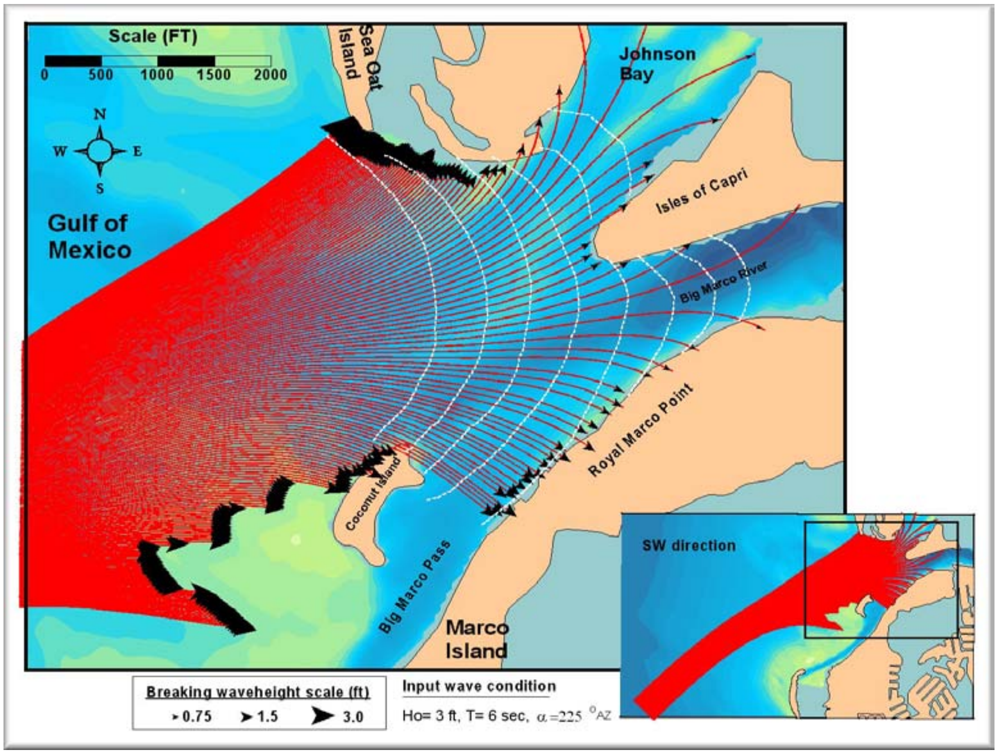

Figure 8. Wave refraction results for SW direction

CAPRI PASS RESERVOIR MODEL APPLICATION

The Inlet Reservoir Model (Kraus 2000a, 2000b) calculates the volume change and bypassing rates for an inlet ebb-shoal complex. Other inlet morphologic features can also be represented. The first step is to identify sediment pathways across the ebb shoal delta and the distinct morphologic features that form the ebb shoal. In a typical wave-dominated inlet, there would be three distinct ocean-side features: an ebb shoal, bypassing bar, and attachment bar. The concept of the Reservoir Model is based on the assumption that each feature has a maximum sand -retention capacity cannot be exceeded. Once a feature has reached capacity, all additional sediment transport to that feature will bypass to the next feature(s), and so forth until sediment arrives at the downdrift side of the inlet or other location, such as the channel and flood shoal. If a morphologic feature is partially full, it still provides (partial) bypassing. The Reservoir Model calculates the growth of the shoals as a function of the littoral drift and the equilibrium volumes of the shoals, and the model accounts for the naturally long timescales of large morphologic features and time delays in transport of material among the features. Detailed discussion of the Reservoir Model can be found in Kraus (2000a, 2000b, 2002).

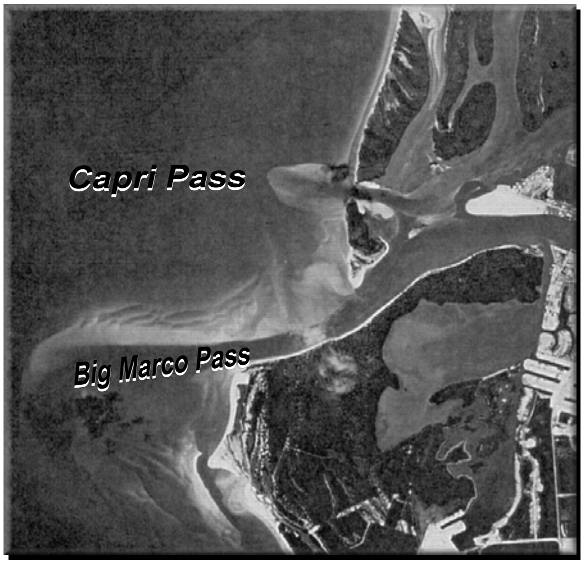

Figure 9. Aerial photo of 1969 conditions

Figure 10. Comparison between 1965 and 2003 conditions

This ebb-shoal system the subject study site is more complex than that of a typical inlet. This is because Capri Pass opened in 1967 near Big Marco Pass, which had a mature ebb shoal for the same tidal prism that is now mainly carried by Capri Pass. During the time the ebb shoal system of Capri Pass was created, the large volume of sand in big Marco Pass was moving onshore. Figure 9 is an aerial photo of the inlet system in 1969, 2 years after the opening of Capri Pass. The extent of the derelict Big Marco Pass Shoal and formation of Capri Pass and shoal are observed. Rapid formation of Capri Pass shoal and slow collapse of Big Marco Pass shoal resulted in an ebb shoal volume in excess of the equilibrium volume as estimated from the tidal prism. Figure 10 shows a comparison between the shoreline of 1965 prior to the pass opening with the 2003 conditions. A large portion of Sea Oat Island has eroded to give way to the growing Capri Pass. Sand from Sea Oat Island contributed to the growth of Capri Pass ebb shoal.

Reservoir Model setup

Establishment of the Reservoir Model for Capri Pass involved several challenges:

1. Unlike typical cases where features grow to an equilibrium volume, some features had decayed or reformed from the derelict Big Marco Pass shoal.
2. More sources of sand contributed to the system than just the littoral drift, including:
    - sand from erosion of Sea Oat Island through opening, widening, and deepening of Capri Pass, and
    - the derelict ebb shoal of Big Marco Pass supplying sand to evolving features and to Marco Island as the shoal collapses (migrates onshore).

The Reservoir Model was enhanced to include an assigned or specified source or drain rate for a given feature. In this way, the supply of sand for eroding shores such Sea Oat Island and derelict features such as 1967-Big Marco Pass ebb shoal can be represented.

Sediment Pathways

The wave, sediment transport, and tidal hydrodynamic modeling, in addition to the bathymetry data, were inspected to define the sediment pathways for this complex inlet system. Figures 11 and 12 show the correlation between ebb current flow and sedimentation patterns indicated by the elevation change between 1994 and 2003.

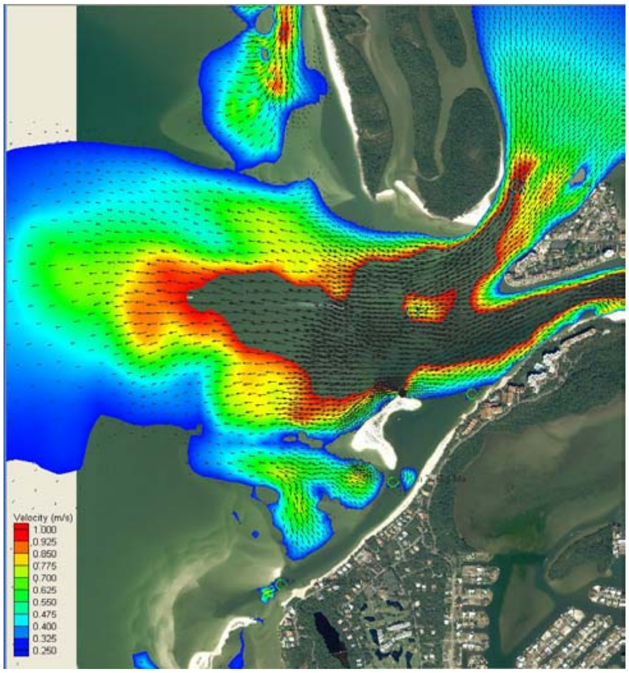

Figure 11. Ebb current velocities

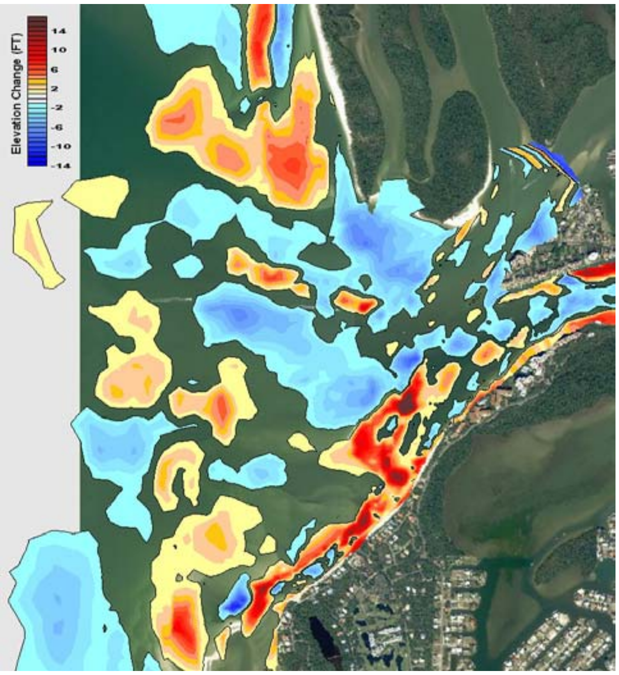

Figure 12. Elevation change (1994-2003)

Figure 11 shows the ebb current flow at the Gulf low water level. Background colors are displayed on for flow below the critical velocity where sediment movement occurs. Figure 12 shows the documented elevation change between 1994 and 2003, yellow and red areas indicate deposition, whereas blue shades indicate erosion or scour.

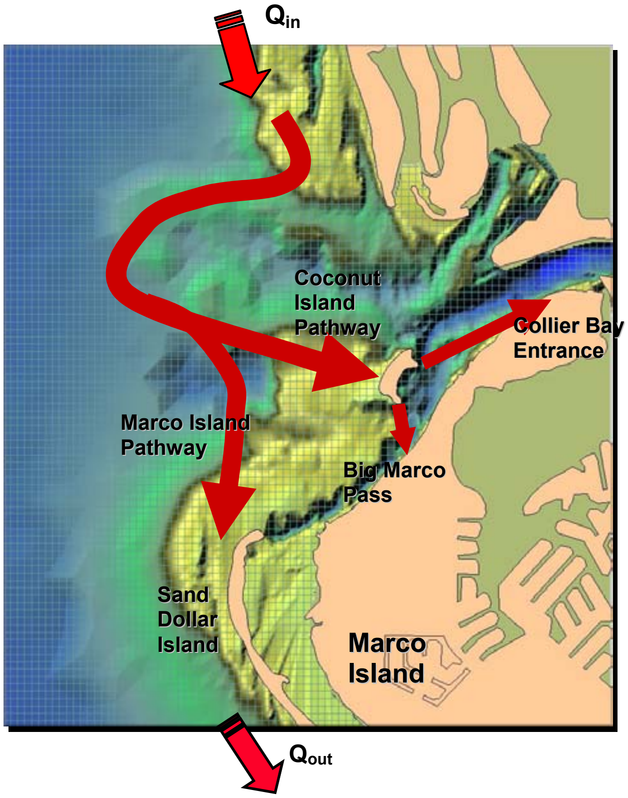

Figure 13. Sediment pathways

Based on the modeling results and documented elevation change, the present-condition sediment pathways for predominant southward transport can be represented as illustrated in Figure 13. As the southward sediment transport bypasses Capri Pass ebb shoal, it follows two separate paths; one towards Coconut Island and the other towards Marco Island attachment bar (Sand Dollar Island). The Coconut Island pathway continues through the two spits at the ends of Coconut Island to bypass some sand to Hideaway Beach and Big Marco Pass. The sand bypassed from the SW spit of Coconut Island continues to fill in the channel of Big Marco Pass. The NE spit bypasses sand to the east end of Hideaway Beach near Collier Bay entrance. The Marco Island pathway bypasses sand to Sand Dollar Island and eventually to the Gulf coastline of Marco Island.

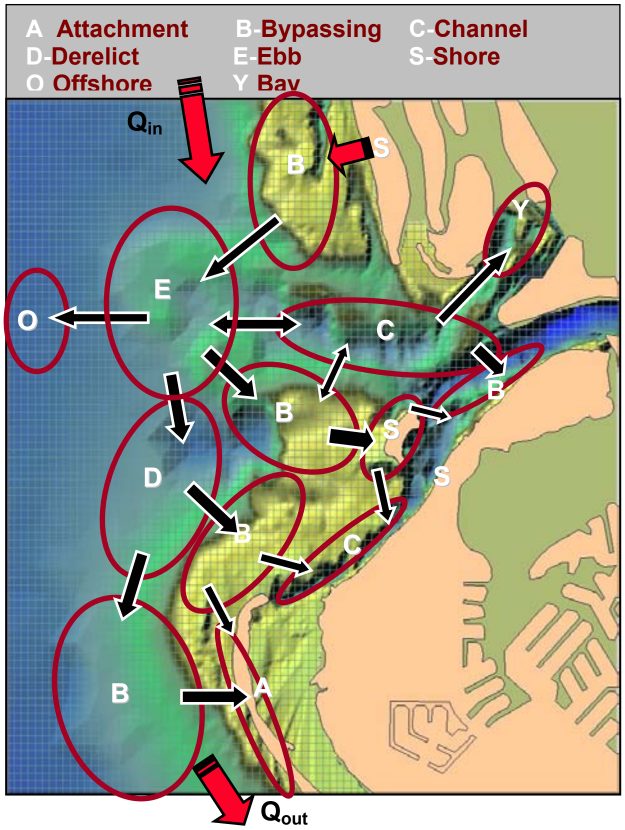

Figure 14. Morphologic features and sediment pathways

Morphologic Features

Defining morphologic features and sediment pathways is central to successful application of the Reservoir Model. Breaking up the ebb shoal complex into several morphologic features was necessary as sediment pathways evolved with morphologic features. The bathymetric data considered together with modeling results defined the distinct morphologic features in the system. The equilibrium volume of each feature was determined based on comparisons of available surveys and calculated volumes and rates of change for each feature. The ebb shoal complex on the south side of Capri Pass was divided into several features to represent the time lag in growth and decay of various features in the system.

Figure 14 shows the morphologic features and sediment pathways for the predominant southward transport direction. Similarly, the northward transport was also represented in the model. The equilibrium volume of each feature was determined based on available surveys and rates of volume change in each feature. The input sediment transport rates were specified as 170,000 cy/year to the south and 100,000 cy/year to the north, based on wave and sediment transport analysis and previous estimates by Van de Kreeke (1990). Other model parameters such as a feature's drain or supply rates were determined based on documented observations and measurements. For instance, Coconut Island drain rate was specified at 18,000 cy/year based on documented erosion rates discussed earlier.

Reservoir Model Results

The measured and calculated volumes for Capri Pass ebb shoal are shown in Figure 15. The results indicate the ebb shoal volume is approaching its equilibrium size of approximately 7 million cy. The measured volumes for the years 2000 and 2003 represent close to approximately 90% of the estimated equilibrium volume.

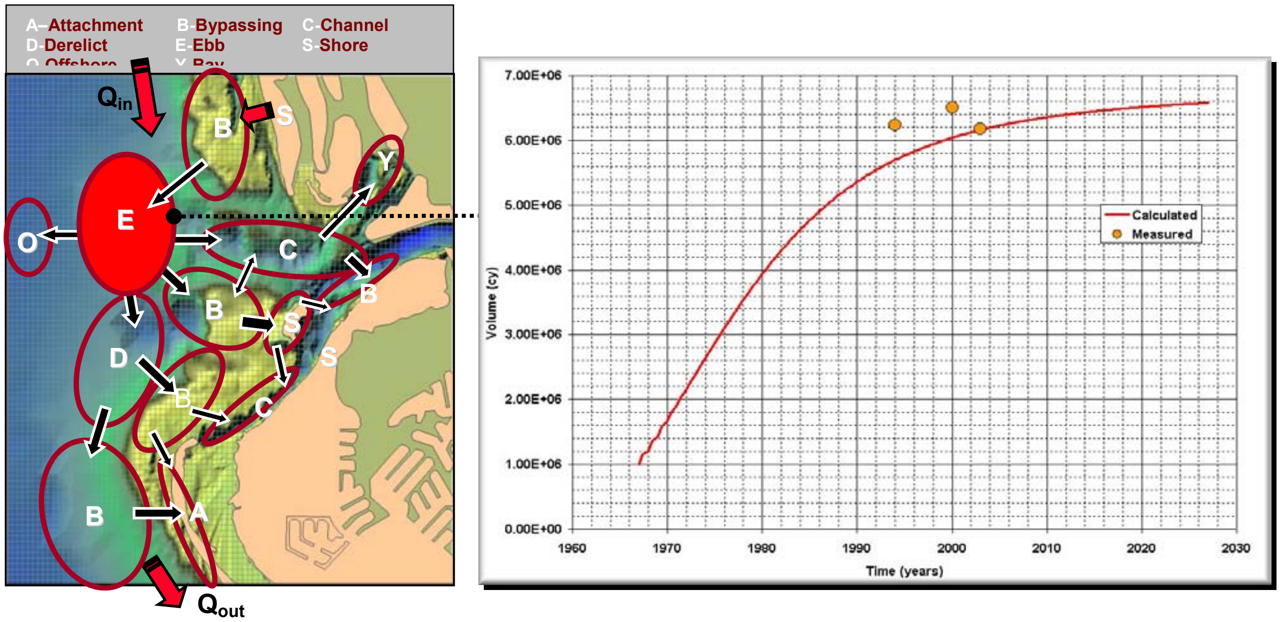

Figure 15. Capri Pass Ebb Shoal volume

Calculated and measured volumes of Coconut Island are shown in Figure 16. The model results match the observed and measured trends of change to Coconut Island. Immediately after the opening of Capri Pass in 1967, Coconut Island was subjected to continuing erosion due to wave action and tidal currents as discussed in Background. In the absence of bypassed material to Coconut Island, erosion and southward migration continued until Coconut Island reached its minimum size in 1988. During this period, the bypassing bar to Coconut Island was forming, and the bypassing rates increasing to begin offsetting the erosion. As the bypassing rates continued to increase, Coconut Island began to grow to its present size. However, the model also predicts future decay of Coconut Island as the bypassed volumes decrease, after the excess volume of the derelict shoal features and sand supply from Sea Oat Island diminish. In addition, sedimentation of Big Marco Pass would reduce the strong tidal currents that are keeping Coconut Island from attaching to Hideaway Beach.

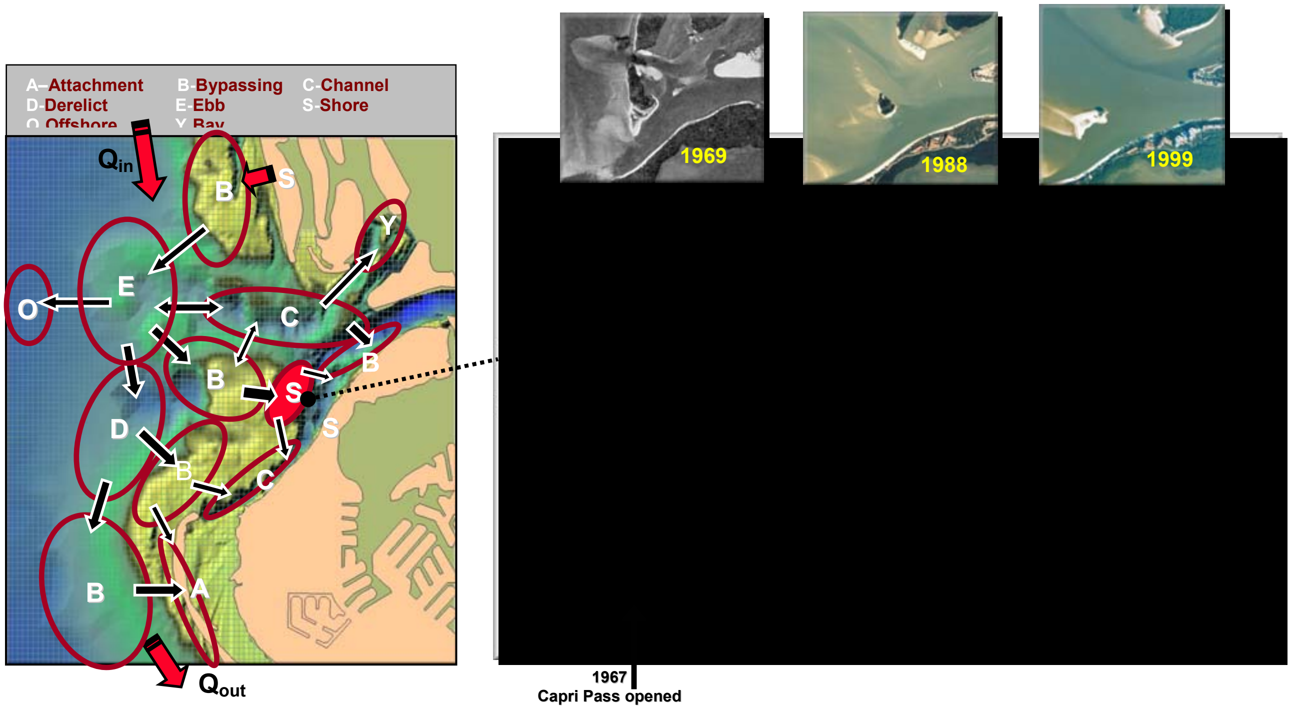

Figure 16. Coconut Island volume

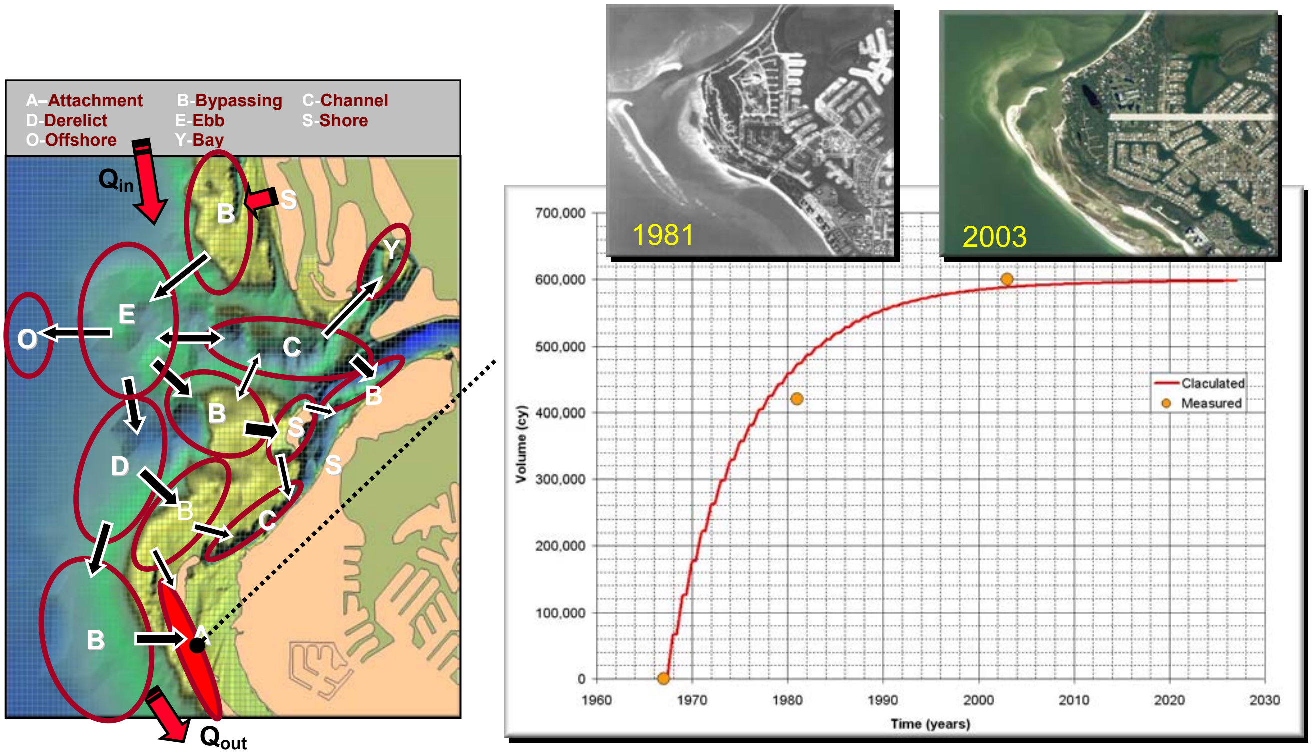

Figure 17. Sand Dollar Island Volume

Figure 17 shows the calculated and measured volumes for the attachment bar "Sand Dollar Island." The measured volumes were determined based on aerial photos and available survey data. The data indicate that Sand Dollar Island emerged by 1980 and continued to grow and migrate shoreward to its current position. The model indicates that the island has reached equilibrium volume and is bypassing sand to Marco Island Gulf-side coast. A sediment drain (decay) rate was not specified for Sand Dollar Island. There is a probability of future decay of Sand Dollar Island, after the sand supply from the derelict ebb shoal of Big Marco Pass is greatly diminished.

Consequence of Mining Capri Pass Ebb Shoal as a Sand Source

Volume measurements and supplementary data were available to validate the Reservoir Model application for Capri Pass. Thus, the model can be operated to evaluate engineering activities such as the proposed use of the ebb shoal as a source for 240,000 cy of sand nourishment to Hideaway Beach. Given the resolution of the model and the possibility of mining larger volume than the design, to conservatively estimate the effects of mining the ebb shoal, removal of 300,000 cy of sand from the ebb shoal was simulated for the year 2004.

Figure 18 shows that removing such volume from the ebb shoal is predicted to set the ebb shoal volume and bypassing rates back approximately 5 years, that is, to their values 5 years before the mining. However, the model does not indicate notable reductions in downdrift bypassing rates. Because the ebb shoal is near its equilibrium volume, removing a relatively small sand volume does not greatly alter the bypass rate – the ebb shoal remains an efficient bypasser for this case.

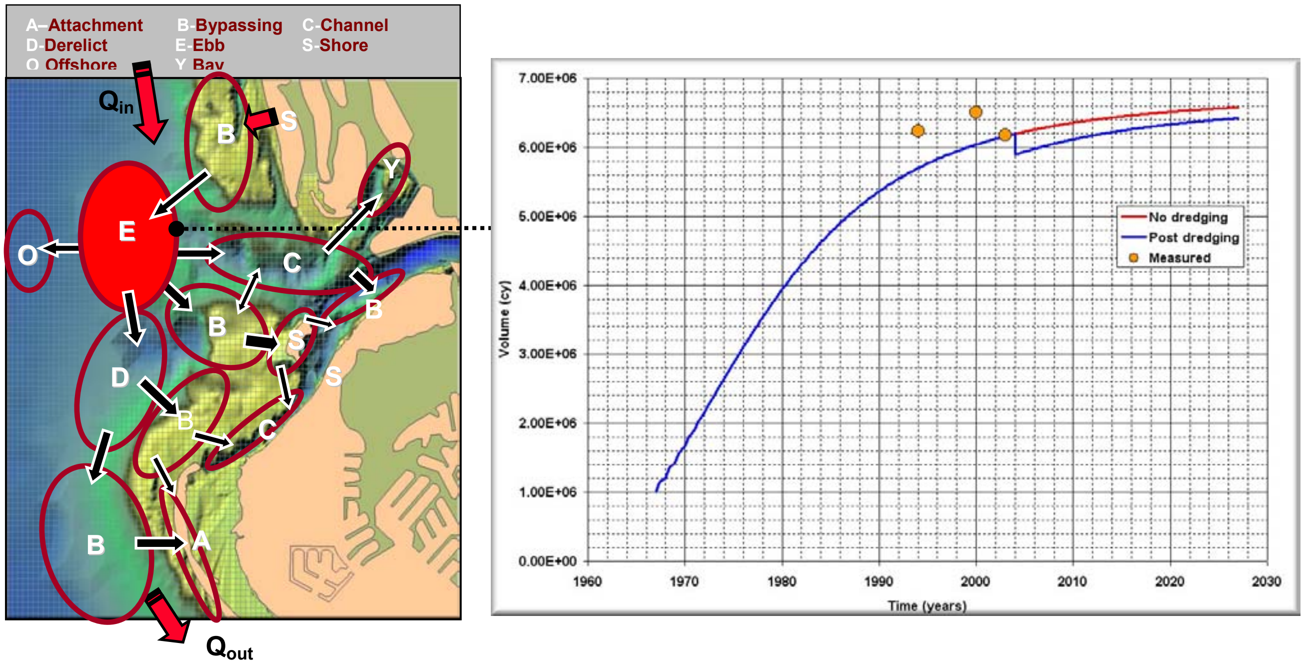

Figure 18. Predicted results of dredging 300,000 cy from Capri Pass ebb shoal

In addition, the mined material is to be placed as beach nourishment on the downdrift side of the inlet, which would tend to offset the decrease in bypassing that might occur. A sand budget analysis based on wave transformation modeling for Hideaway Beach indicated that approximately 4,000 cy/year is transported west of south point to Sand Dollar Island and downdrift beaches (H&M 2003). That amount is projected to increase during the lifetime of the nourishment project, which is on the same order of magnitude as the recovery time of the ebb shoal, 6 years, projected by the Reservoir Model.

DISCUSSION AND CONCLUSIONS

Morphologic features of tidal inlets, such as ebb shoals and flood shoals, are attractive potential sources of sediment for nourishment of beaches because of their close proximity to shore and the probable compatibility of sediment grain size and color with the neighboring beaches. Morphologic features on an inlet, however, participate as part of integrated natural bypassing system. Mining of a particular feature such as an ebb shoal will reduce the rate of supply of sediment to connected features and ultimately to the down-drift beach in the bypassing system. The natural sediment-bypassing rate will be re-established to the pre-mining rate only after the mined feature returns to the volume at the time of mining.

From an inlet management perspective, key questions to be address in considering inlet shoal mining are: (1) what will be the reduction in the bypassing rate to the down-drift beach, (2) How long will it take for the mined feature to return to its volume prior to mining, and (3) what are the reductions to the transport rates to other morphologic features of the system? Analytical tools are becoming available to answer these questions, and this paper has demonstrated such a methodology through application of wave refraction modeling, tidal circulation modeling, and modeling of inlet natural bypassing and volume change in response to mining. Through availability of bathymetry data and aerial photographs to document beach and inlet morphology change, reliable representation of natural bypassing in the Inlet Reservoir Model could be achieved, with sediment pathways inferred in part through understanding of wave-generated and tidal currents.

The Inlet Reservoir Model was applied to evaluate the evolution of the complex inlet system of Capri Pass and assess the consequences of mining its ebb shoal as a sand source. Capri Pass is the major tidal inlet of a multi-inlet system located at the north end of Marco Island, Florida, on the Gulf of Mexico coastline. Capri Pass opened in 1967 near Big Marco Pass, which had a mature ebb shoal for the same tidal prism that is now mainly carried by Capri Pass. The rapid formation of Capri Pass shoal and slow collapse of Big Marco Pass shoal resulted in an ebb shoal volume in excess of the equilibrium volume as estimated from the tidal prism.

The available bathymetric data considered together with wave, sediment transport, and tidal hydrodynamic modeling results defined the sediment pathways and the distinct morphologic features in the system. Identification and division of the ebb shoal complex into several morphologic features was necessary to represent sediment pathways as they evolved with the morphologic features. The Reservoir Model was enhanced to include an assigned or specified source or drain rate for a given feature to enable the representation of eroding shores and derelict features.

The Reservoir Model application for Capri Pass was validated with volume measurements and supplementary data. The model was operated to evaluate the proposed use of the ebb shoal as a source for 240,000 cy of sand nourishment to Hideaway Beach at the down drift side of the inlet. The Reservoir Model provided a quantitative tool to assess the effects of the proposed dredging and optimize sand management for the multi-inlet system.

ACKNOWLEDGEMENTS

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APPENDIX A. REGIONAL HYDRODYNAMIC MODELING

The tidal hydrodynamics of the multiple-inlet system of Little Marco Pass, Capri Pass, and Big Marco Pass were modeled using the **Ad**vanced **Circ**ulation (ADCIRC) model (Luettich, et al 1991). The modeling was performed to evaluate the tidal circulation and sediment transport patterns. The model covered the bay areas of big Marco River and Johnson Bay that contribute to the tidal prism flowing through the multiple inlet system. The coverage extends more than 8 miles alongshore and 4.5 miles offshore to include the ebb shoals and nearshore bottom features and represent the Gulf boundary water surface elevation. The grid boundaries were set far from the inlet system to provide regional modeling of the three interacting inlets connected to the Big Marco River and Johnson Bay.

The ADCIRC grid for this study encompassed 63,339 nodes and 121,816 elements. The grid varied from lower resolution at the Gulf boundary to high resolution in the nearshore and inlet regions. Node spacing ranged from 300 m at the offshore boundary to 10 m for the high resolution areas. Figure A1 shows the regional ADCIRC grid, and Figure A2 shows grid and bathymetry details of Capri Pass and Big Marco Pass. The model driving forces were the Gulf of Mexico water level fluctuations resulting from astronomical tide. The water levels were computed based on tidal constituents (K1, O1, P1, Q1, M2, S2, N2, and K2) from Le Provost, et al. (1994) database. The simulation date was chosen to represent average tide range and a 2-day run was simulated with a time step of 1 sec.

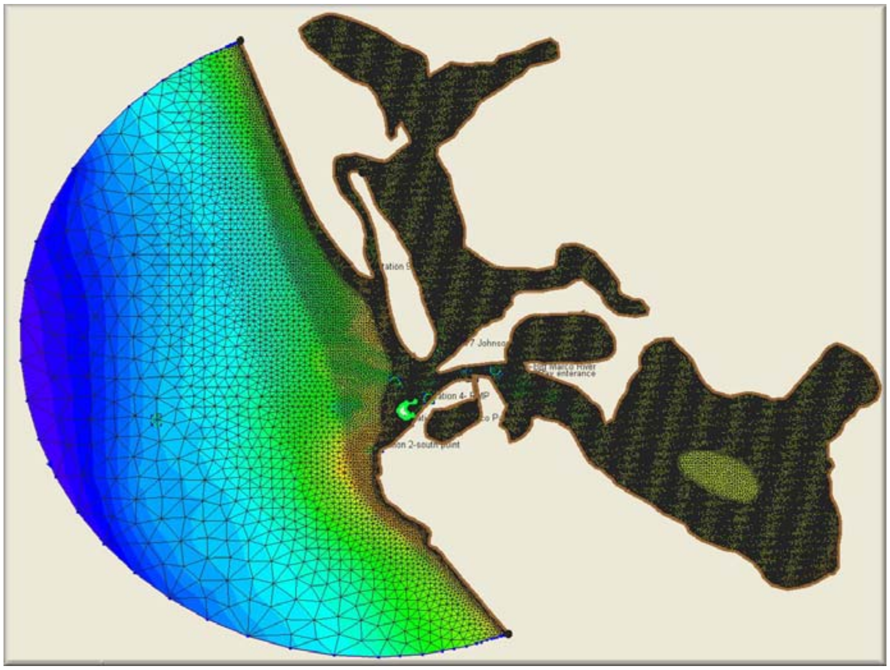

Figure A1. ADCIRC Regional model area

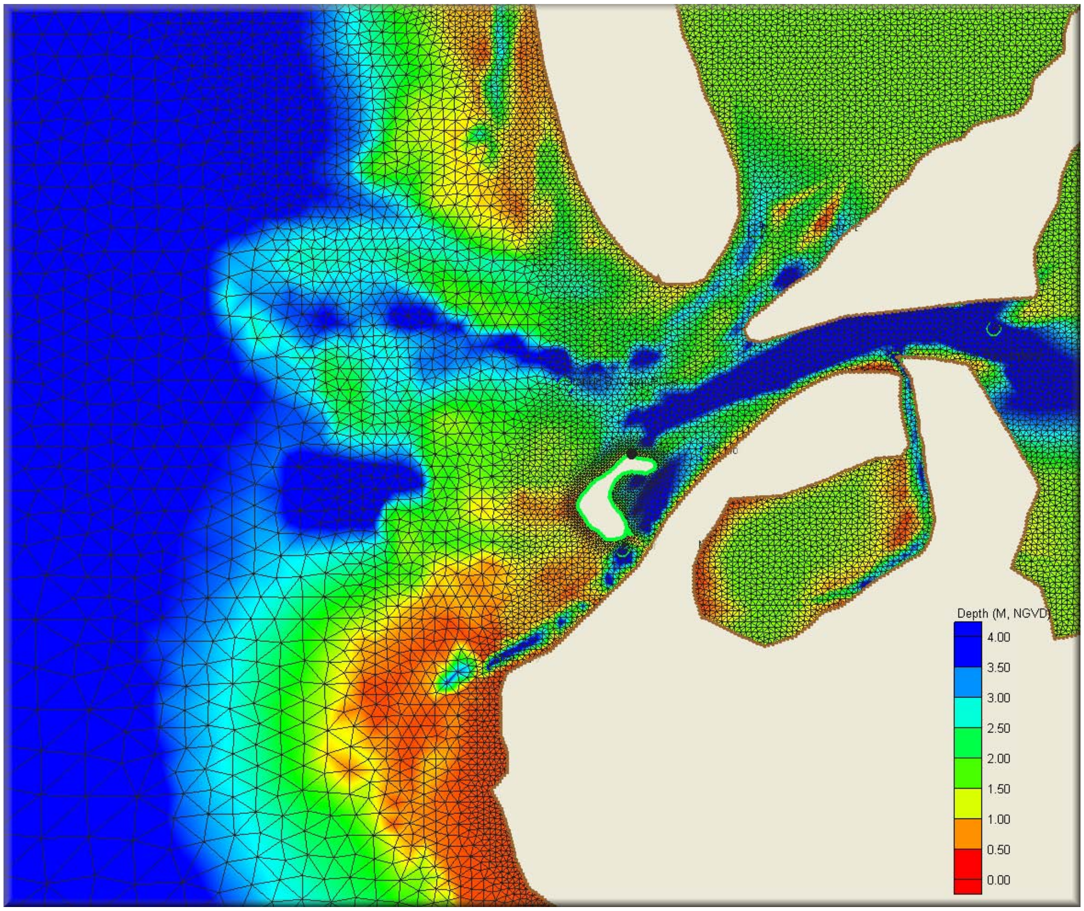

Figure A2. ADCIRC grid details at Capri Pass and Big Marco Pass

Figures A3 and A4 show computed flood and ebb currents respectively. Velocity magnitude background colors were selected to identify morphologic change in response to the tidal current. Red color areas indicate velocities greater than the critical velocity for sediment deposition. Littoral drift transported to red colored areas is carried by the strong tidal currents and deposited in areas where velocities are below the critical velocity (areas between red and blue).

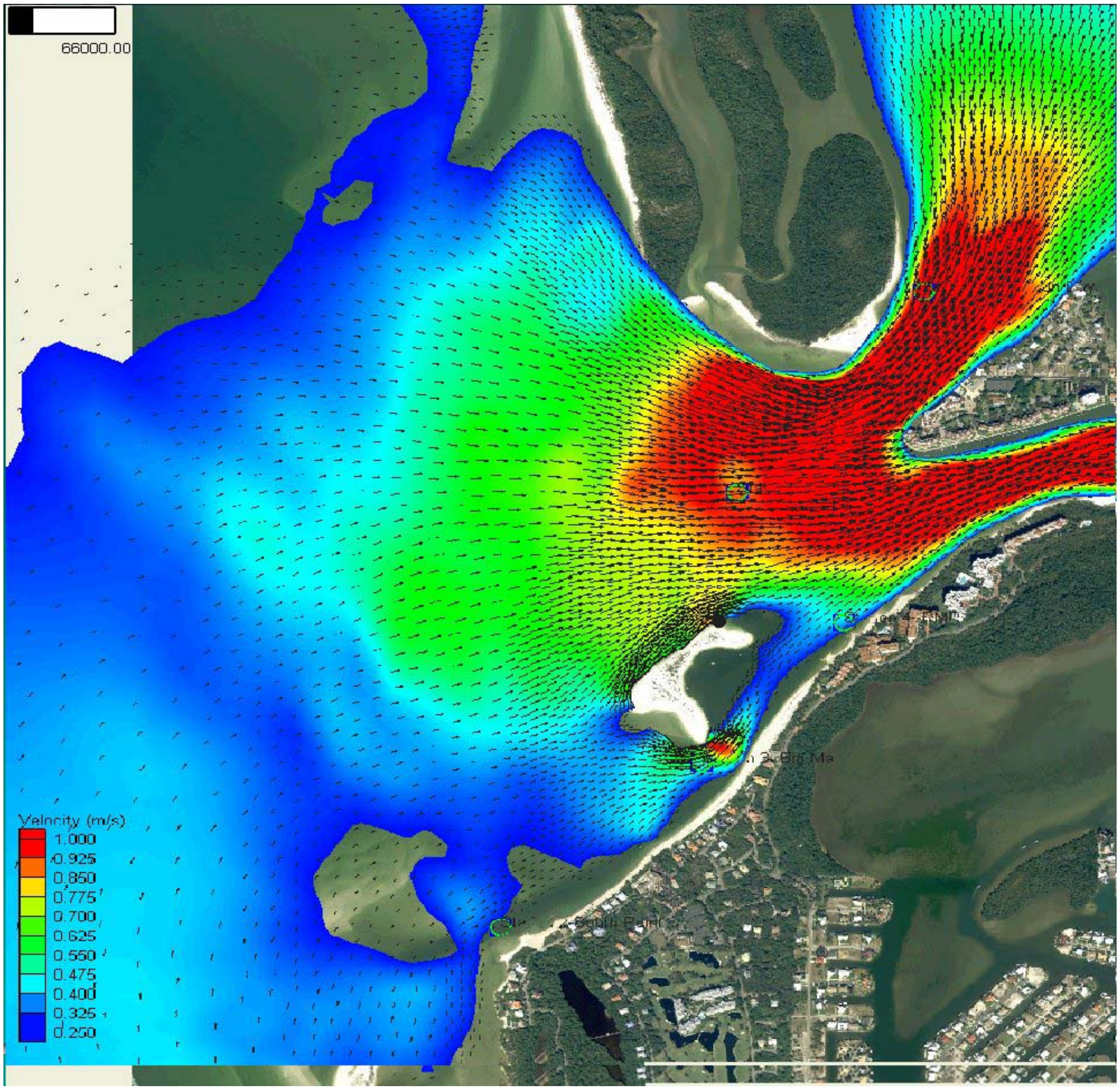

Figure A3. Calculated flood tidal current

The results indicate that the currents at the SW spit of Coconut Island are strong enough to keep Coconut Island from attaching. However, the results also show the ebb current through Big Marco Pass flows more around Coconut Island into the Gulf rather than through the channel of Big Marco Pass. The preference around Coconut Island explains the sedimentation (Shoaling) of Big Marco Pass and the reduced share of tidal prism flowing through it. The ADCIRC model results for this regional multi-inlet system indicated that the percentage of tidal prism flowing through Little Marco Pass, Capri Pass, and Big Marco Pass are 7, 90% and 3%, respectively.

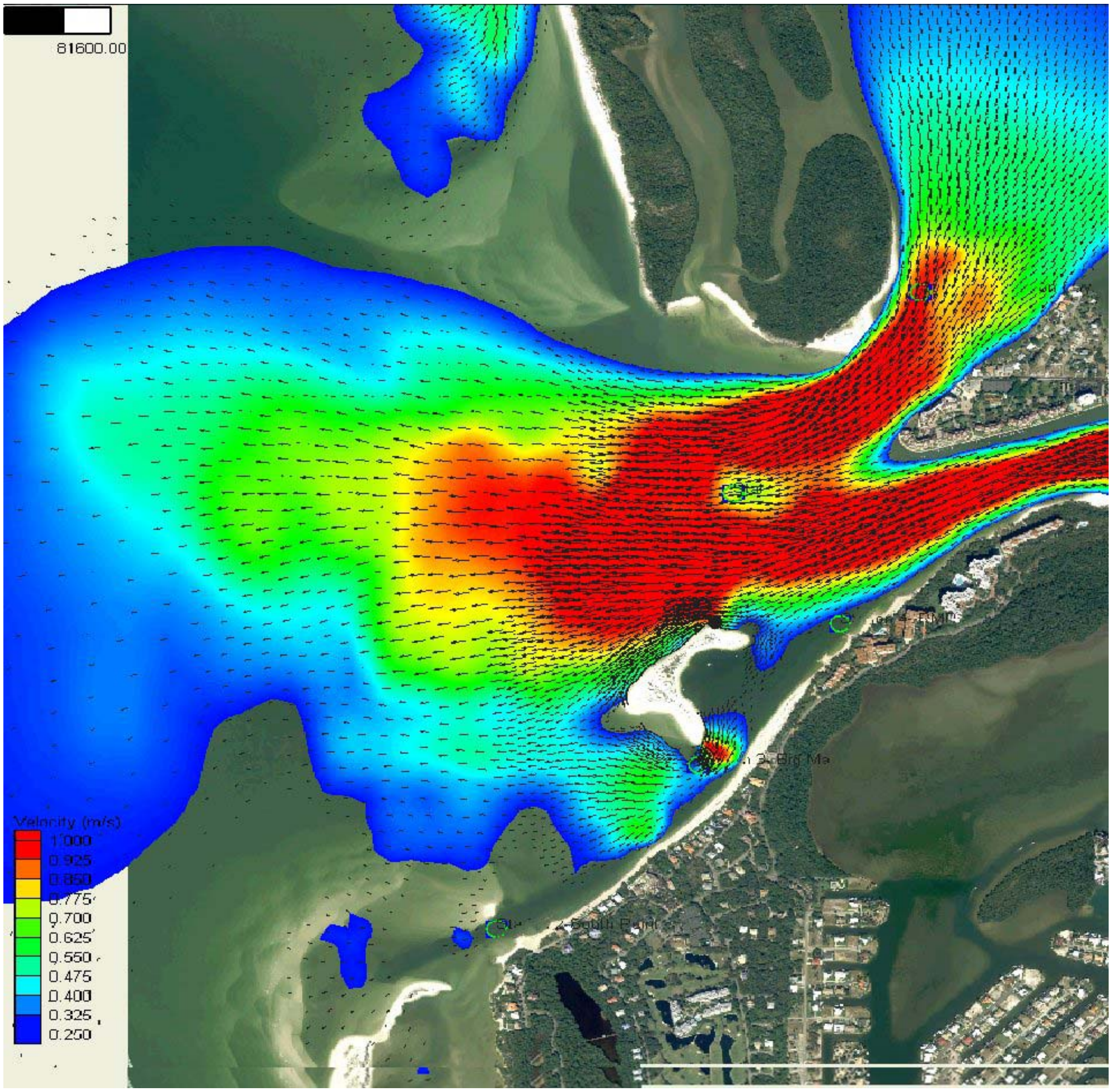

Figure A4. Calculated ebb tidal current